

# Kaon Production in Heavy-Ion Collisions and Kaon Condensation in Neutron Stars\*

*G.Q. Li, C.-H. Lee, and G.E. Brown*

Physics Department, State University of New York at Stony Brook, Stony Brook, New York 11794, USA

The recent past witnesses the growing interdependence between the physics of hadrons, the physics of relativistic heavy-ion collisions, and the physics of compact objects in astrophysics. A notable example is the kaon which plays special roles in all the three fields. In this talk, we first review the various theoretical investigations of kaon properties in nuclear medium. We then present a detailed transport model study of kaon production and flow in heavy-ion collisions at SIS energies. Finally, We discuss the effects of the kaon in-medium properties extracted from heavy-ion data on neutron star properties, especially on the lowering of maximum mass of neutron stars with the onset of kaon condensation around  $3\rho_0$ .

## I. INTRODUCTION

There is currently growing interplay between physics of hadrons (especially the properties of hadrons in dense matter which might reflect spontaneous chiral symmetry breaking and its restoration), the physics of relativistic heavy-ion collisions (from which one might extract hadron properties in dense matter), and the physics of compact objects in astrophysics (which needs as inputs the information gained from the first two fields). A notable example is the kaon ( $K$  and  $\bar{K}$ ), which, being a Goldstone boson with strangeness, plays a special role in all the three fields mentioned.

Ever since the pioneering work of Kaplan and Nelson [1] on the possibility of kaon condensation in dense nuclear matter, many works have been devoted to the study of kaon properties in nuclear matter. There are two typical approaches to this problem, one based on the chiral perturbation theory [2–9], and the other based on the extension of the Walecka-type mean field model from  $SU(2)$  to  $SU(3)$  [10,11]. Although quantitatively, the results from these different models are not completely identical, qualitatively, a consistent picture, namely in nuclear matter the kaon feels a weak repulsive potential and the antikaon feels a strong attractive potential, has emerged.

Measurements of kaon spectra and flow have been systematically carried out in heavy-ion collisions at SIS (1-2 AGeV), AGS (10 AGeV), and SPS (200 AGeV) energies [12]. Of special interest is kaon production in heavy-ion collisions at SIS energies, as it has been shown that particle production at subthreshold energies is sensitive to its properties in dense matter [13–15].

Studies of neutron star properties also have a long history. A recent compilation by Thorsett quoted by Brown [16] shows that well-measured neutron star masses are all less than  $1.5M_\odot$ . On the other hand, most of the theoretical calculations based on conventional nuclear equation of state (EOS) predict a maximum neutron state mass above  $2M_\odot$ . The EOS can, therefore, be substantially softened without running into contradiction with observation. Various scenarios have been proposed that can lead to a soft EOS. Brown and collaborators suggested that kaon condensation might happen at a critical density of  $2-4\rho_0$  [17].

In the first part of this talk we review various theoretical approaches for studying kaon properties in nuclear medium. In the second part we present a detailed analysis of kaon production in heavy-ion collisions at SIS energies. By comparing transport model predictions with experimental data, we try to extract kaon in-medium properties at high densities. This information provides guidance for the study of kaon condensation in neutron stars, which is the focus of the third part of the talk.

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## II. KAON IN DENSE MATTER: A REVIEW

The interactions between pseudoscalar meson and baryon are usually described by the  $SU(3)_L \times SU(3)_R$  nonlinear chiral Lagrangian. In the mean-field approximation and including only the Weinberg-Tomozawa and the Kaplan-Nelson terms, the kaon and antikaon energies are given by

$$\omega_{K,\bar{K}} = \left[ m_K^2 + \mathbf{k}^2 - \frac{\Sigma_{KN}}{f^2} \rho_S + \left( \frac{3\rho_N}{8f^2} \right)^2 \right]^{1/2} \pm \frac{3\rho_N}{8f^2}. \quad (1)$$

Note that the scalar attraction depends on nucleon scalar density  $\rho_S$ , which is model dependent [10]. The scalar attraction is proportional to the kaon-nucleon sigma term,  $\Sigma_{KN}$ , which can be related to pion-nucleon sigma term,  $\Sigma_{\pi N}$ . The latter is relatively well determined to be about 45 MeV. There are, unfortunately, large uncertainties in the strange quark mass and nucleon strangeness content. There are also a number of corrections to these simple mean-field results, such as the range terms which reduce the scalar attraction [7], the Brown-Rho scaling in  $f_\pi$  [18,19], which cancels approximately the short-range correlation effects [20], and the coupled channel effects in the case of  $K^-$  [9,21]. A detailed discussion on these can be found in Ref. [22].

In view of large uncertainties in  $\Sigma_{KN}$  and difficulties in treating systematically high-order corrections, we adopt here a more phenomenological approach. We assume that the effects from the scaling in  $f_\pi$  and short-range correlations approximately cancel each other. Furthermore, we introduce two free parameters,  $a_K$  and  $a_{\bar{K}}$ , which determine the scalar attractions for  $K^+$  and  $K^-$ . The kaon and antikaon energy in the nuclear medium can then be written as

$$\omega_{K,\bar{K}} = [m_K^2 + \mathbf{k}^2 - a_{K,\bar{K}}\rho_S + (b_K\rho_N)^2]^{1/2} + b_K\rho_N, \quad (2)$$

where  $b_K = 3/(8f_\pi^2) \approx 0.333 \text{ GeVfm}^3$ . We try to determine  $a_K$  and  $a_{\bar{K}}$  from the experimental observables in heavy-ion collisions.

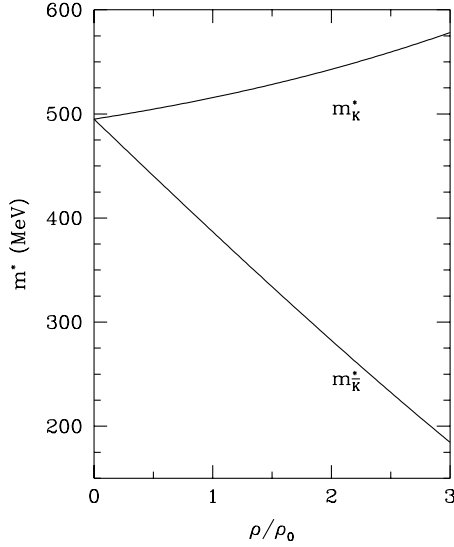


FIG. 1. Effective masses of kaon and antikaon.

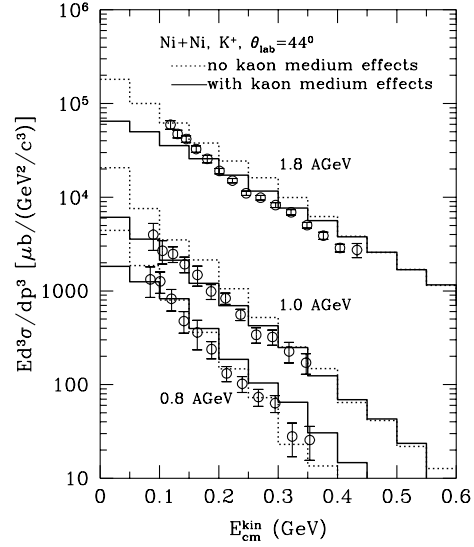


FIG. 2.  $K^+$  kinetic energy spectra.

Since the kaon-nucleon interaction is relatively weak as compared to other hadron-nucleon interactions, impulse approximation is considered to be reasonable for the kaon potential in nuclear matter, at least at low densities. This provides some constraint on  $a_K$ . Using  $a_K = 0.22 \text{ GeV}^2\text{fm}^3$ , we find that at normal

nuclear matter density  $\rho_0 = 0.16 \text{ fm}^{-3}$ , the  $K^+$  feels a repulsive potential of about 20 MeV. This is in rough agreement with what is expected from the impulse approximation using the  $KN$  scattering length in free space. Determination of the  $a_{\bar{K}}$  is more delicate, as impulse approximation does not apply. We find that  $a_{\bar{K}} = 0.45 \text{ GeV}^2 \text{ fm}^3$  provides a good fit to the  $K^-$  data in heavy-ion collisions at SIS energies. With these two parameters we show in Fig. 1 the effective masses of kaon and antikaon defined as their energies at zero momentum. It is seen that the kaon mass increases slightly with density, while that of the antikaon drops substantially.

### III. KAON PRODUCTION IN HEAVY-ION COLLISIONS

One of the most important ingredients in the transport model study of particle production in heavy-ion collisions is the elementary particle production cross sections in hadron-hadron interactions. At SIS energies, the colliding system consists mainly of nucleons, delta resonances, and pions. We need thus kaon and antikaon production cross sections from nucleon-nucleon ( $NN$ ), nucleon-delta ( $N\Delta$ ), delta-delta ( $\Delta\Delta$ ), pion-nucleon ( $\pi N$ ), and pion-delta ( $\pi\Delta$ ) interactions. In addition, the antikaon can also be produced from strangeness-exchange processes such as  $\pi Y \rightarrow \bar{K}N$ . Because of the lack of experimental data, especially near production threshold that are important for heavy-ion collisions at SIS energies, we have to adopt the strategy that combines the parameterization of experimental data with some theoretical investigations and reasonable assumptions and prescriptions. A comprehensive analysis of these elementary cross section can be found in Ref. [22].

Particles produced in elementary hadron-hadron interactions in heavy-ion collisions cannot escape the environment freely and be detected. Instead, they are subjected to strong final-state interactions. For the kaon, because of strangeness conservation, its scattering with nucleons at low energies is dominated by elastic and pion production processes, which do not affect its final yield but changes its momentum spectra. The final-state interaction for the antikaon is much stronger. As mentioned, antikaons can be destroyed in the strangeness-exchange processes. They also undergo elastic scattering.

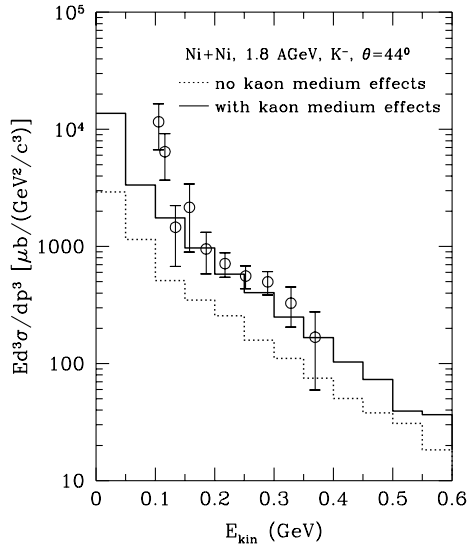


FIG. 3.  $K^-$  kinetic energy spectra.

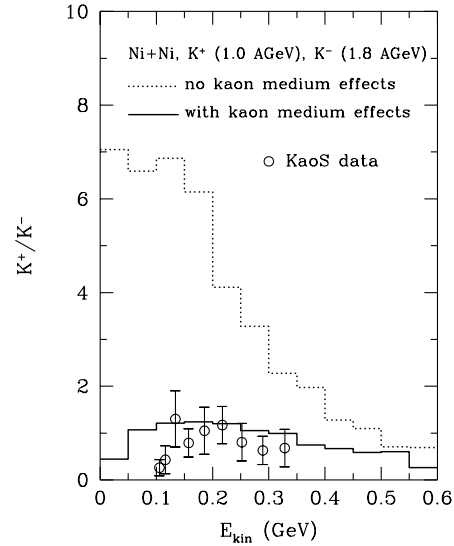


FIG. 4.  $K^+/K^-$  ratio as a function of kinetic energy.

The results for  $K^+$  kinetic energy spectra in Ni+Ni collisions at 0.8, 1.0 and 1.8 AGeV are shown in Fig. 2. The solid histogram gives the results with kaon medium effects, while the dotted histogram is the results without kaon medium effects. The open circles are the experimental data from the KaoS

collaboration [23]. It is seen that the results with kaon medium effects are in good agreement with the data, while those without kaon medium effects slightly overestimate the data. We note that kaon feels a small repulsive potential; thus the inclusion of the kaon medium effects reduces the kaon yield. The slopes of the kaon spectra in the two cases also differ. With a repulsive potential, kaons are accelerated during the propagation, leading to a larger slope parameter as compared to the case without kaon medium effects.

The results for the  $K^-$  kinetic energy spectra are shown in the middle window Fig. 3 for Ni+Ni collision at 1.8 AGeV. It is seen that without medium effects, our results are about a factor 3-4 below the experimental data. With the inclusion of the medium effects which reduces the antikaon production threshold, the  $K^-$  yield increases by about a factor of 3 and our results are in good agreement with the data. This is similar to the findings of Cassing *et al.* [24]. Also, with the inclusion of kaon medium effects, the slope parameter of the  $K^-$  spectra decreases, since the propagation of antikaons in their attractive potential reduces their momenta.

The medium effects on kaon and antikaon can be best seen by looking at their ratio as a function of kinetic energy. This is shown Fig. 4. Without kaon medium effects, the  $K^+/K^-$  ratio decreases from about 7 at low kinetic energies to about 1 at high kinetic energies. Since the antikaon absorption cross section by nucleons increases rapidly at low momentum, low-momentum antikaons are more strongly absorbed by nucleons than high-momentum ones. This makes the  $K^+/K^-$  ratio increase with decreasing kinetic energies. When medium effects are included, we find that the  $K^+/K^-$  ratio is almost a constant of about 1 in the entire kinetic energy region, which is in good agreement with the experimental data from the KaoS collaboration [23], shown in the figure by open circles.

Another observable that can probe kaon potential in dense matter more clearly is kaon flow, which is not affected by the uncertainties in the elementary cross sections [25]. The results for  $K^+$  flow in Ni+Ni collisions from different transport models are compared with experimental data [26] in Figs. 5. The results shown in the left window are obtained without kaon potential, while those in the right window include the kaon potential. The solid, dashed, and dotted curves are from Refs. [25], [27], and [28], respectively. It is seen that, within the experimental errorbars, the results with a weak repulsive kaon potential is in better agreement with the data.

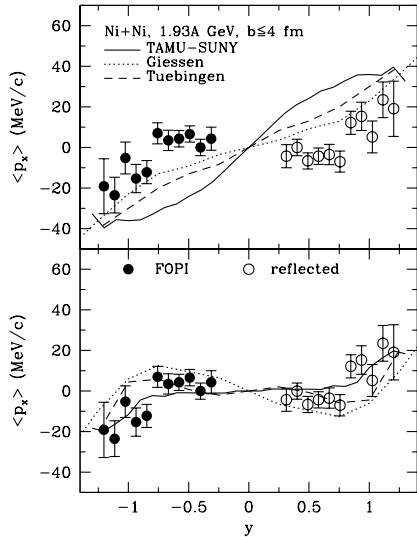


FIG. 5.  $K^+$  flow from different calculations

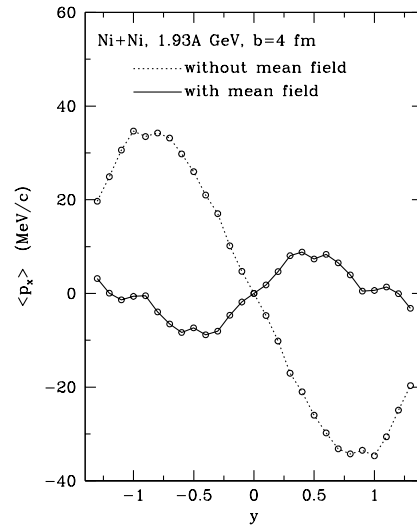


FIG. 6.  $K^-$  flow in Ni+Ni collisions.

Similarly one can analyse  $K^-$  flow. The results from Ref. [29] are shown in Fig. 6. The solid and dashed curves are obtained with and without  $K^-$  potential, respectively. Without kaon potential, we see that antikaons flow in the opposite direction to that of nucleon, simply because of the strong absorption of

antikaons by spectator nucleons. Once the attractive  $K^-$  potential is turned on, those surviving antikaons are pulled towards nucleons, resulting in a weak flow signal. Primary experimental data seem to be in better agreement with the scenario with antikaon potential.

#### IV. KAON CONDENSATION IN NEUTRON STARS

As mentioned, the medium modification of kaon properties affects not only kaon observables in heavy-ion collisions, it also bears important consequences in the structure and evolution of compact objects in astrophysics, especially the maximum mass of neutron stars. In the presence of kaons, the chemical equilibrium conditions require that the chemical potentials should satisfy

$$\mu = \mu_n - \mu_p = \mu_e = \mu_\mu = \mu_{K^-}. \quad (3)$$

The local charge neutrality can be imposed by minimizing the thermodynamical potential

$$\Omega = \varepsilon_N + \varepsilon_{K^-} + \varepsilon_L - \mu(\rho_p - \rho_{K^-} - \rho_e - \rho_\mu). \quad (4)$$

For the energy density of nucleons we use the results of Furnstahl, Tang, and Serot [30]. The energy density  $\varepsilon$  of the ground state of the system is obtained by extremizing  $\Omega$ . The pressure of the system is then obtained from the energy density. They are then used in the TOV equation to obtain the properties of neutron stars. The pressure as a function of energy density for both the cases with and without kaons are shown in Fig. 7.

The results for neutron star mass as a function of central density  $\rho_{cent}$  are shown in Fig. 8. It is seen that, without kaons, the maximum neutron star mass in this model is about  $2M_\odot$ . Similar conclusions, with neutron star mass in the range of  $2.1\text{--}2.3M_\odot$ , have been obtained in Ref. [31] based on the nuclear equation of state from the Dirac-Brueckner-Hartree-Fock approach. When kaons are included, the maximum mass of neutron stars is about  $1.5M_\odot$ .

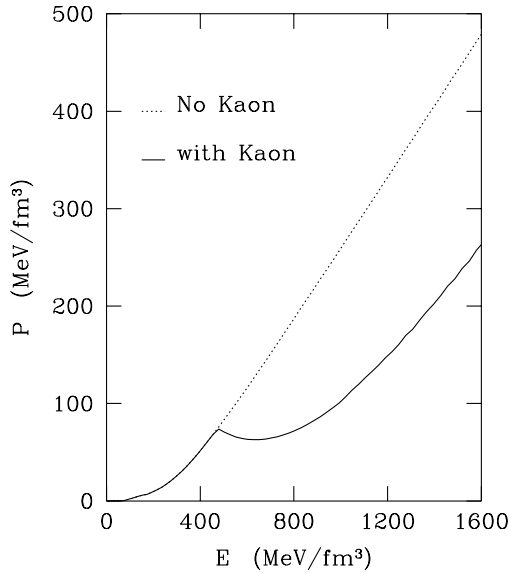


FIG. 7. Equation of state of neutron star matter.

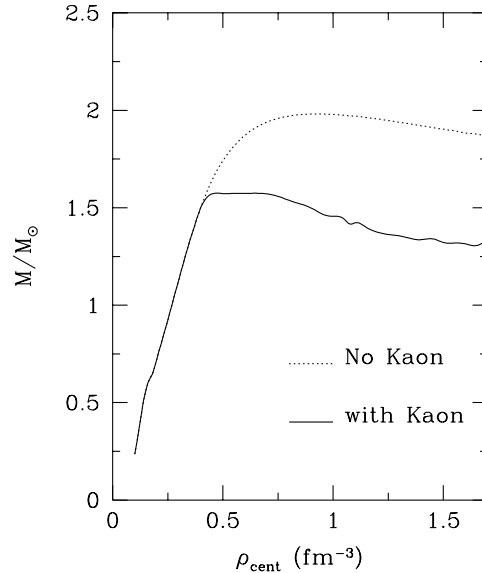


FIG. 8. Neutron star mass as a function of central density

## V. SUMMARY AND OUTLOOK

In summary, we studied  $K^+$  and  $K^-$  production in Ni+Ni collisions at 1-2 AGeV, based on the relativistic transport model including the strangeness degrees of freedom. We found that the recent experimental data from the KaoS collaboration are consistent with the predictions of the chiral perturbation theory that the  $K^+$  feels a weak repulsive potential and  $K^-$  feels a strong attractive potential in nuclear medium. Using the kaon in-medium properties constrained by the heavy-ion data, we have studied neutron star properties with and without kaon condensation. The maximum mass of neutron stars is found to be about  $2.0M_\odot$  based on conventional nuclear equations of state obtained from the effective Lagrangian of Furnstahl *et al.*. This can be reduced to about  $1.5M_\odot$ , once kaon condensation is introduced. We have emphasized the growing interdependence between hadron physics, relativistic heavy-ion physics and the physics of compact stars in astrophysics.

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